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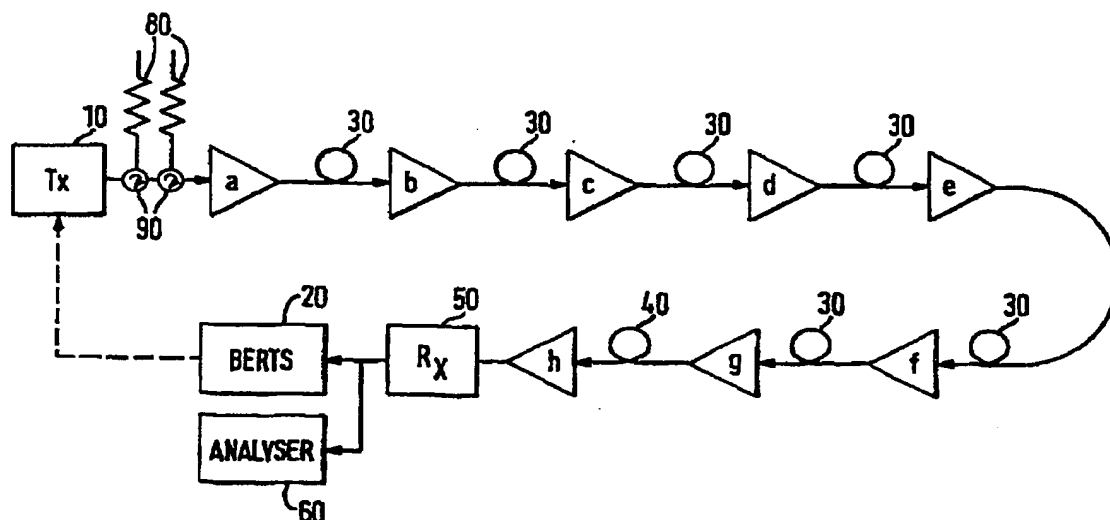
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(54) **COMPENSATION DE DISPERSION DANS UNE TRANSMISSION  
PAR FIBRES OPTIQUES**

(54) **DISPERSION COMPENSATION IN OPTICAL FIBRE  
TRANSMISSION**



(57) L'invention concerne un appareil de transmission optique, pour la transmission de signaux optiques à une longueur d'onde optique d'environ 1550 nanomètres. Cet appareil comprend une liaison de fibres optiques monomodales constituée de fibres optiques présentant une dispersion sensiblement égale à zéro, à une longueur d'onde optique d'environ 1300 nanomètres et une dispersion d'environ 17 picosecondes par nanomètre-kilomètre, à une longueur d'onde optique d'environ 1550 nanomètres. Cet appareil comporte, en outre, un ou plusieurs réseaux de fibres optiques à fluctuation de l'élargissement d'une impulsion et compensation de

(57) Optical transmission apparatus, for transmission of optical signals at an optical wavelength of about 1550 nanometres, comprises: a single mode optical fibre link formed of optical fibre having substantially zero dispersion at an optical wavelength of about 1300 nanometres and a dispersion of about 17 picoseconds per nanometre-kilometre at an optical wavelength of about 1500 nanometres; and one or more dispersion compensating chirped optical fibre gratings, the aggregate dispersion of the chirped optical fibre gratings substantially compensating for the dispersion of the optical fibre link; in which the one or more gratings are



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dispersion, la dispersion totale du réseau de fibres optiques à fluctuation de l'élargissement d'impulsion compensant sensiblement la dispersion de la liaison de fibres optiques. Dans cet appareil, un ou plusieurs réseaux sont couplés à la liaison de fibres optiques, en des positions respectives sensiblement symétriques, disposées autour du centre longitudinal de la liaison de fibres optiques.

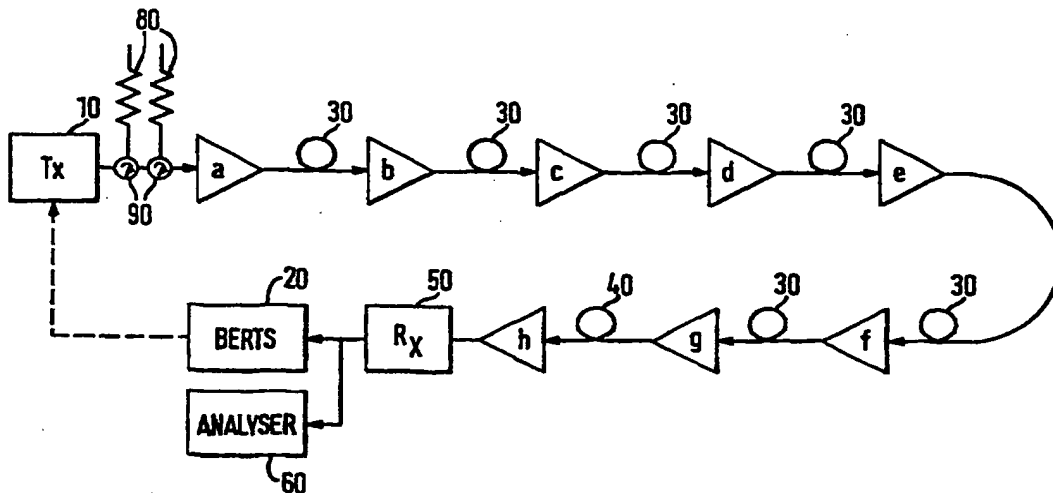
coupled to the optical fibre link at respective positions substantially symmetrically disposed about the longitudinal centre of the optical fibre link.

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(54) Title: DISPERSION COMPENSATION IN OPTICAL FIBRE TRANSMISSION



## (57) Abstract

Optical transmission apparatus, for transmission of optical signals at an optical wavelength of about 1550 nanometres, comprises: a single mode optical fibre link formed of optical fibre having substantially zero dispersion at an optical wavelength of about 1300 nanometres and a dispersion of about 17 picoseconds per nanometre-kilometre at an optical wavelength of about 1500 nanometres; and one or more dispersion compensating chirped optical fibre gratings, the aggregate dispersion of the chirped optical fibre gratings substantially compensating for the dispersion of the optical fibre link; in which the one or more gratings are coupled to the optical fibre link at respective positions substantially symmetrically disposed about the longitudinal centre of the optical fibre link.

DISPERSION COMPENSATION IN OPTICAL FIBRE TRANSMISSION

This invention relates to dispersion compensation in optical fibre transmission.

5 Data transmission in optical fibres is generally limited by power loss and pulse dispersion. The advent of erbium-doped fibre amplifiers (EDFAs) has effectively removed the loss limitation for systems operating in the third optical communication window (around a wavelength of about  $1.55\mu\text{m}$  (micrometer)), leaving pulse dispersion as a serious limitation, especially in future high-capacity multi-wavelength optical networks.

10 More importantly, most fibre which has already been installed for telecommunication links (ie. standard non- dispersion shifted fibre) exhibits a dispersion zero around  $1.3\mu\text{m}$  and thus exhibits high (about  $17\text{ps/nm.km}$  (picosecond per nanometre-kilometre)) dispersion around  $1.55\mu\text{m}$ . Upgrading this fibre to higher bit rates involves the use of EDFAs and a shift in operating wavelength to  $1.55\mu\text{m}$  where dispersion-compensation becomes a necessity.

15 Several techniques have been demonstrated including laser pre-chirping, mid-span spectral-inversion (phase-conjugation), the addition of highly-dispersive compensating fibre and chirped fibre gratings. Chirped fibre gratings are of particular interest, since they are compact, low-loss and offer high negative-dispersion of arbitrary and tunable profile.

20 When one or more chirped fibre gratings are used to provide dispersion compensation in an optical fibre link, they introduce an associated optical signal loss. It has therefore been proposed that the grating(s) should be used at an input end of an optical fibre link, preferably followed by an optical amplifier, so that the optical power launched into the link can be restored to a desired level after pre-compensation by the chirped grating(s). This previous proposal makes use of the fact that dispersion compensation of an optical pulse launched into a dispersive optical fibre link can be applied as a pre-compensation before the pulse enters the link because the dispersion and dispersion compensation are linear effects.

25 30 It is a constant aim to improve dispersion compensation techniques in optical fibre transmission systems, and particularly in systems which have already been installed using the so-called standard telecom fibre defined above. In such installed

systems, any improvements must be made by discrete components rather than by using a different type of fibre for the transmission link.

This invention provides optical transmission apparatus for transmission of optical signals at an optical wavelength of about 1550 nanometres, the apparatus comprising:

5 a single mode optical fibre link formed at least in part of optical fibre having substantially zero dispersion at an optical wavelength of about 1300 nanometres and a dispersion of about 17 picoseconds per nanometre-kilometre at an optical wavelength of about 1550 nanometres; and

10 one or more dispersion compensating chirped optical fibre gratings, the aggregate dispersion of the chirped optical fibre gratings substantially compensating for the dispersion of the optical fibre link;

in which the one or more gratings are coupled to the optical fibre link at respective positions substantially symmetrically disposed about the longitudinal centre  
15 of the optical fibre link.

The invention recognises that there is a difference in the performance of an optical link of the so-called standard telecom fibre when used at 1550nm, depending on the positioning of the gratings. This difference is not predicted by the previously accepted linear effect of dispersion compensation. In such a linear system, it would  
20 not matter where the gratings were positioned.

A physical reason for the dependence on grating positioning is that the peak optical power at positions along the fibre link varies in dependence on where the dispersion compensation is performed. This peak optical power then determines the non-linear response of the fibre links.

25 As optical pulses propagate along an optical fibre, the fibre dispersion causes different wavelengths to travel at different velocities. The effect of this on a single gaussian pulse would simply be to broaden the pulse in the time domain, thus lowering the instantaneous peak power. However, in a train of pulses (as in a real communications link), each individual pulse can be time-broadened into the bit period  
30 for an adjacent pulse, so there can be times when, locally, the peak optical power actually exceeds the peak power launched into the fibre.

By counter-intuitively distributing the dispersion compensation at intervals

systems, any improvements must be made by discrete components rather than by using a different type of fibre for the transmission link.

Optics Letters Vol. 19, No. 17, 1994, pp 1314-1316 is an early paper on dispersion compensation using chirped fibre gratings. No teaching is given on the position of the gratings in the link to be compensated. EP-A-0 684 709 discloses a dispersion compensation arrangement using dispersion-compensating optical fibres.

This invention provides optical transmission apparatus for transmission of optical signals at an optical wavelength of about 1550 nanometres, the apparatus comprising:

a single mode optical fibre link formed at least in part of optical fibre having substantially zero dispersion at an optical wavelength of about 1300 nanometres and a dispersion of about 17 picoseconds per nanometre-kilometre at an optical wavelength of about 1550 nanometres; and

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along the fibre, the maximum dispersion of the pulse train at any point along the fibre link is lower than if the dispersion compensation were provided simply at the input or output of the link. This leads to a lower maximum local peak optical power along the link, and so to an improvement in non-linear distortion along the link.  
5 Ultimately, this improvement can lead to longer (or cheaper) links being possible for the same dispersion compensating and amplifying components.

This invention therefore goes against conventional teaching, which would suggest that if the optical pulses are pre-dispersed, the optical power would be "smeared out" and so the peak optical power would be reduced. In fact, it has been  
10 found that the opposite can happen.

The invention is also distinct from systems employing, for example, lengths of dispersion compensating optical fibre as dispersion compensating devices. In such previous systems, fibre non-linearity has not been regarded as a problem.

It will be appreciated by the skilled man that the exact positioning of components in an optical fibre link may depend on the ease of access to the link (which may, for example, be underground) and so components may be positioned within, say, 10% of the approximate positions specified above while still falling within the advantageous arrangement of embodiments of the invention. Similarly, the skilled man will appreciate the slight latitude in the definition of "standard" telecom  
15 fibre used above.  
20

Preferably each such grating is connected to the link by an optical circulator.

Apparatus according to the invention is particularly usefully employed in optical communication apparatus also comprising: an optical transmitter connected to an input end of the optical transmission apparatus, the optical transmitter being  
25 operable to generate optical signals at an optical wavelength of about 1550 nanometres and an optical receiver connected at an output end of the optical transmission apparatus, the optical receiver being operable to receive optical signals at an optical wavelength of about 1550 nanometres.

The invention will now be described by way of example only with reference  
30 to the accompanying drawings in which:

Figure 1 is a schematic diagram of an optical fibre transmission link;

Figure 2a is a schematic representation of an eye diagram.



Figure 2b is a schematic graph of eye closure penalty against transmission link length; and

Figure 3 is a schematic graph of peak optical power at six positions along the transmission link of Figure 1.

5 Referring now to Figure 1, an optical fibre transmission link comprises an optical transmitter 10, in this example operating under the control of a bit error rate (BER) test set (BERTS) 20. The transmitter operates at an optical wavelength of  $1.55 \mu\text{m}$  to generate substantially chirp-free, non-return-to-zero (NRZ) pulses at 10 Gbit/s (gigabits per second). The pulses have a raised cosine profile in the time domain so  
10 that the optical intensity from a single pulse representing a binary "1" falls to zero at the centre of the bit period for adjacent bits.

The optical output of the optical transmitter 10 is connected to a series of optical amplifiers (denoted by a, b, c, d, e, f, g and h) between which are respective  
15 100 km (kilometre) spans 30 of so-called standard telecom optical fibre, exhibiting (as described above) high dispersion at  $1.55 \mu\text{m}$ .

At the output of the final amplifier in the series, amplifier g, there is a further variable length span 40 of the standard telecom fibre. This supplies an optical signal to an optical receiver 50, which in turn is electrically connected to the BERTS 20. Thus, the BERTS 20 generates bit patterns to be converted into an optical signal by  
20 the transmitter 10, and then compares the output of the optical receiver 50 with the intended bit pattern to detect bit errors which have occurred in transmission via the optical link.

The specific details of the components shown in Figure 1 are as follows. The optical fibre dispersion is  $17 \text{ ps}/(\text{nm.km})$ , the fibre loss  $0.23 \text{ dB/km}$ , the fibre non-linear refractive index coefficient  $n_2$   $2.6 \times 10^{-20} \text{ m}^2/\text{W}$ , and the effective core area  $80 \mu\text{m}^2$ . The gain of each optical amplifier a..h is substantially linear and is set so that  
25 the average optical power launched into the following fibre span 30, 40 is  $+6 \text{ dBm}$ . The receiver 50 comprises a  $125 \text{ GHz}$  bandwidth optical filter followed by a square-law optical detector. The resulting electrical signal is electrically filtered by a third  
30 order Butterworth filter with a  $10 \text{ GHz}$   $3\text{dB}$  bandwidth. The BERTS generates a 256-bit random bit sequence.

The electrical output of the receiver 50 is also connected to an analyser 60

which, using known techniques, provides an eye diagram representing the transmission properties of the optical link. Eye diagrams are well known and will not be discussed in detail here. However, to define the terms to be used in this description, Figure 2a illustrates a schematic eye diagram and shows the eye opening 100. This eye opening can be measured with and without the optical fibre spans and associated components (such as the gratings to be described below) in place. (i.e. the eye opening can be measured in a "back-to-back" configuration where the optical transmitter is connected directly to the optical receiver). In this description, the "eye penalty" for a particular configuration of the optical link is defined as the ratio (expressed in decibels (dB)) of the eye opening in the back-to-back configuration to the eye opening with the link in that configuration. A numerically larger eye penalty implies a worse link performance.

In the present arrangement, two identical dispersion chirped optical fibre compensating gratings 80, each providing equivalent compensation to the dispersion of 300km of the optical fibre, are connectable by series-inserted optical circulators 90 at various points in the link. In Figure 1 the gratings are shown both connected at the input of amplifier a (the output could just as easily be used), but in fact they are separately connectable at the inputs (outputs) of any of the amplifiers a..h. For the experiments/simulations described below, the gratings 80 were connected in four configurations:

- aa both gratings connected at the input of amplifier a (in fact as shown in Figure 1)
- ah one grating at the input of amplifier a and one at the input of amplifier h
- ce one grating at the input of amplifier c and one at the input of amplifier e (i.e. at 1/3 and 2/3 positions along the length of the link when the span 40 was set to zero)
- dd both gratings connected at the input of amplifier d

Figure 2b is a schematic graph of eye closure penalty against transmission link length for the three grating configurations ah, dd and ce, and Figure 3 is a schematic

graph of peak optical power at six positions along the transmission link for the four grating configurations aa, ag, ce and dd. In fact the graphs of Figures 2b and 3 have been obtained by numerical simulation of the link of Figure 1, but the main conclusions have also been confirmed by experiment.

5 For Figure 2b, the length of the fibre span 40 was allowed to increase to enable values to be obtained for overall link lengths over 600km. For Figure 3, the length of the span 40 was set to zero. Because of the constraints on amplifier outputs described here, this meant that for Figure 3 the amplifier h had a substantially 0dB net gain.

10 Figure 2b demonstrates that, of the configurations shown, the best (lowest) eye closure penalty is obtained when the two gratings are at amplifiers c and e. Also, the configuration dd (in which the two gratings effectively form a single dispersion compensator for the whole 600km link and are functionally equivalent to a single grating disposed at the centre of the link and capable of compensating the dispersion  
15 of the whole 600km link) is still significantly better than an arrangement in which the gratings are at the beginning and end of the link (ag).

This principle has been extended by other experiments to show that it is most desirable to employ an optical fibre transmission link comprising two or more optical fibre spans of substantially equal length, in which a respective dispersion  
20 compensating device is connected between adjacent pairs of the fibre spans. Here, the compensating device(s) should substantially compensate for the dispersion of  $1 + 1/(n-1)$  fibre spans, where  $n$  is the number of spans in the link. For example, in a three-span link having two fibre gratings disposed at  $1/3$  and  $2/3$  of the way along the link (as in the configuration ce), each grating should substantially compensate for  $1 + 1/2$  spans of the fibre, i.e. half of the total length of the link.  
25

This same principle also applies to an optical fibre transmission link comprising two or more dispersion compensating devices connected to the link at positions substantially symmetrically disposed about the longitudinal centre of the link.

30 This difference in link performance depending on the positioning of the gratings is not predicted by the previously accepted linear effect of dispersion compensation. In such a linear system, it would not matter where the gratings were

positioned.

A physical reason for the dependence on grating positioning noted here is that the peak optical power at positions along the fibre link varies in dependence on where the dispersion compensation is performed. This peak optical power then determines the non-linear response of the fibre links.

As optical pulses propagate along an optical fibre, the fibre dispersion causes different wavelengths to travel at different velocities. The effect of this on a single gaussian pulse would simply be to broaden the pulse in the time domain, thus lowering the instantaneous peak power. However, in a train of pulses, each individual pulse can be time-broadened into the bit period for an adjacent pulse, so there can be times when, locally, the peak optical power actually exceeds the peak power launched into the fibre.

Figure 3 is a schematic graph showing this variation in peak power along the 600km link of Figure 1 (the six 100km sections 30 between amplifier a and amplifier g), with the dispersion compensating gratings in configurations aa, ag, dd and ce. The average power is set to +6dBm at the output of each amplifier. The curves aa, ag, ce and dd are different because of the different temporal distribution of optical power caused by the dispersion effects, which in turn leads to a different instantaneous distribution of peak optical power.

Curves ce and dd start the same at the left hand side of Figure 3, but at 200km into the link (the position (c) of the first grating in configuration ce), the curves diverge with curve dd showing a greater peak power than curve ce. Curves

It can be seen that the maximum value of the local peak power is lowest for the configuration ce, followed by the curve dd. Curves aa and ah show much higher levels of peak power.

The lower peak powers given by configurations ce and dd lead to lower levels of non-linear distortion in the fibre and so to better (lower) eye closure penalties at the receiver.

CLAIMS

1. Optical transmission apparatus for transmission of optical signals at an optical wavelength of about 1550 nanometres, the apparatus comprising:

5 a single mode optical fibre link (30) formed at least in part of optical fibre having substantially zero dispersion at an optical wavelength of about 1300 nanometres and a dispersion of about 17 picoseconds per nanometre-kilometre at an optical wavelength of about 1550 nanometres; and

10 one or more dispersion compensating chirped optical fibre gratings, the aggregate dispersion of the chirped optical fibre gratings substantially compensating for the dispersion of the optical fibre link;

characterised in that the one or more gratings are coupled to the optical fibre link at respective positions substantially symmetrically disposed about the longitudinal centre of the optical fibre link.

15

2. Apparatus according to claim 1, in which each of the one or more gratings is connected to the optical fibre link by a respective optical circulator.

3. Apparatus according to claim 1 or claim 2,  
20 in which the optical fibre link comprises two or more serially connected optical fibre sections (30), a respective optical amplifier (a, b, c, d, e, f, g) being disposed between serially adjacent fibre sections.

4. Apparatus according to any one of the preceding claims, the apparatus having  
25 one dispersion compensating optical fibre grating for substantially compensating the dispersion of the whole link and being coupled to the link substantially at the longitudinal centre of the link.

5. Apparatus according to any one of claims 1 to 3, the apparatus having two  
30 dispersion compensating optical fibre gratings respectively coupled to the link at longitudinal positions of substantially one third and substantially two thirds of the length of the link.

6. Apparatus according to any one of claims 1 to 3, the apparatus having two dispersion compensating optical fibre gratings respectively coupled to the link at an input end of the link and at an output end of the link.

5 7. Apparatus according to any one of the preceding claims, in which the link has a length of under 1000 kilometres.

8. Optical communication apparatus comprising:

optical transmission apparatus according to any one of claims 1 to 7;

10 an optical transmitter (10) connected to an input end of the optical transmission apparatus, the optical transmitter being operable to generate optical signals at an optical wavelength of about 1550 nanometres and

an optical receiver (50) connected at an output end of the optical transmission apparatus, the optical receiver being operable to receive optical signals at an optical  
15 wavelength of about 1550 nanometres.

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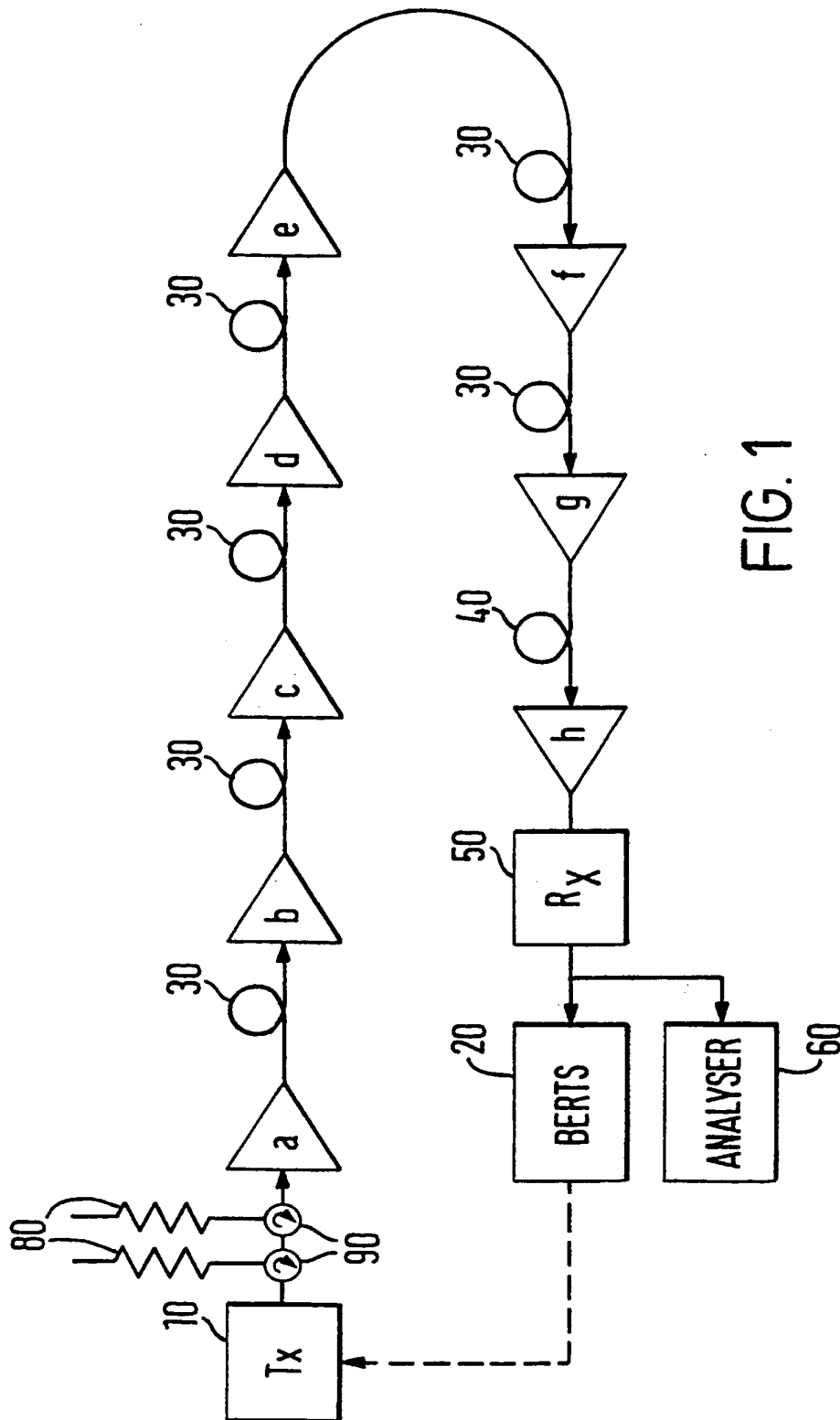


FIG. 1

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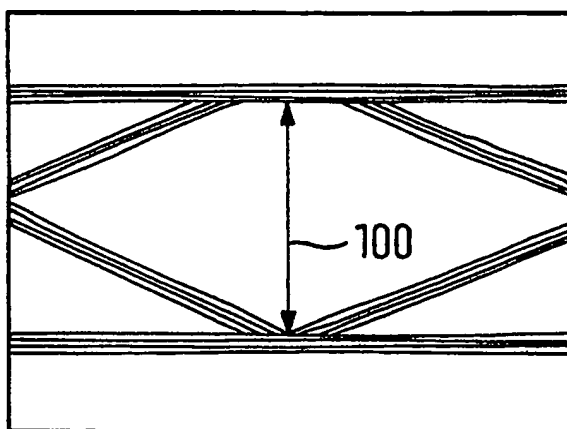


FIG. 2a

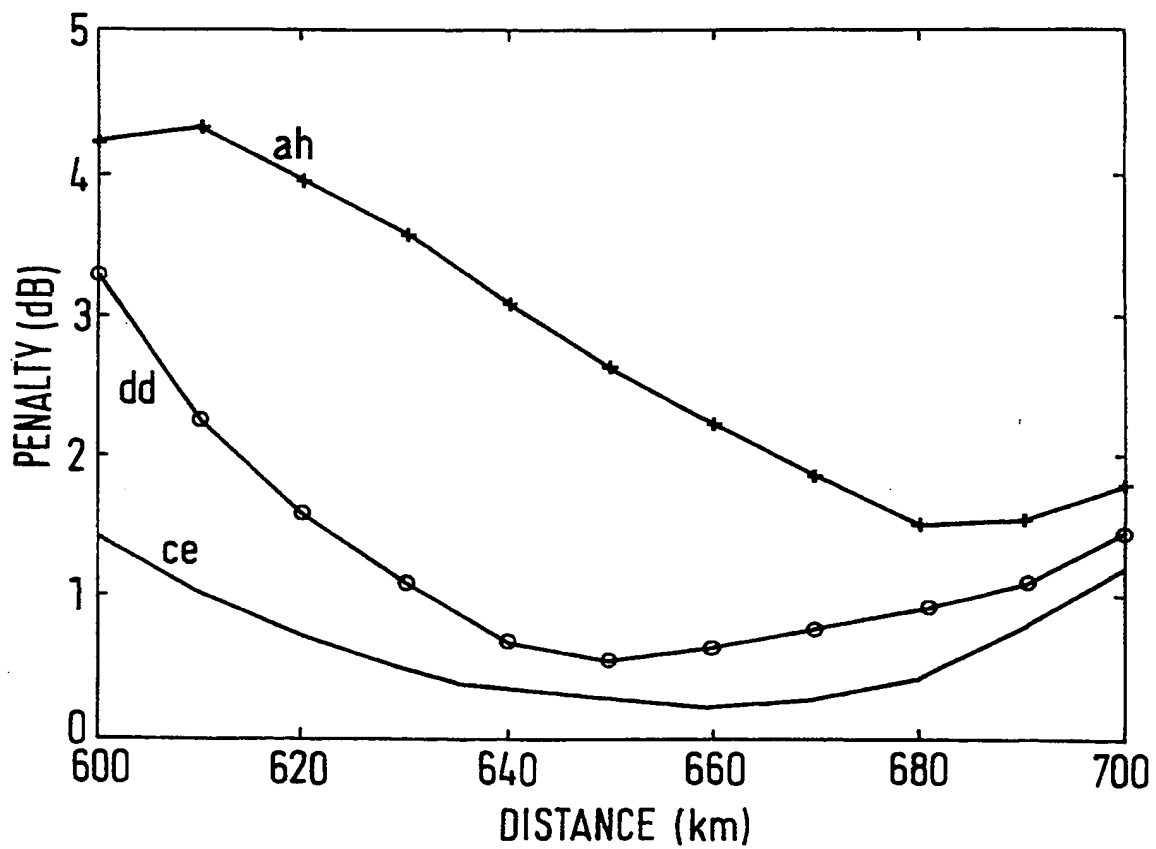


FIG. 2b



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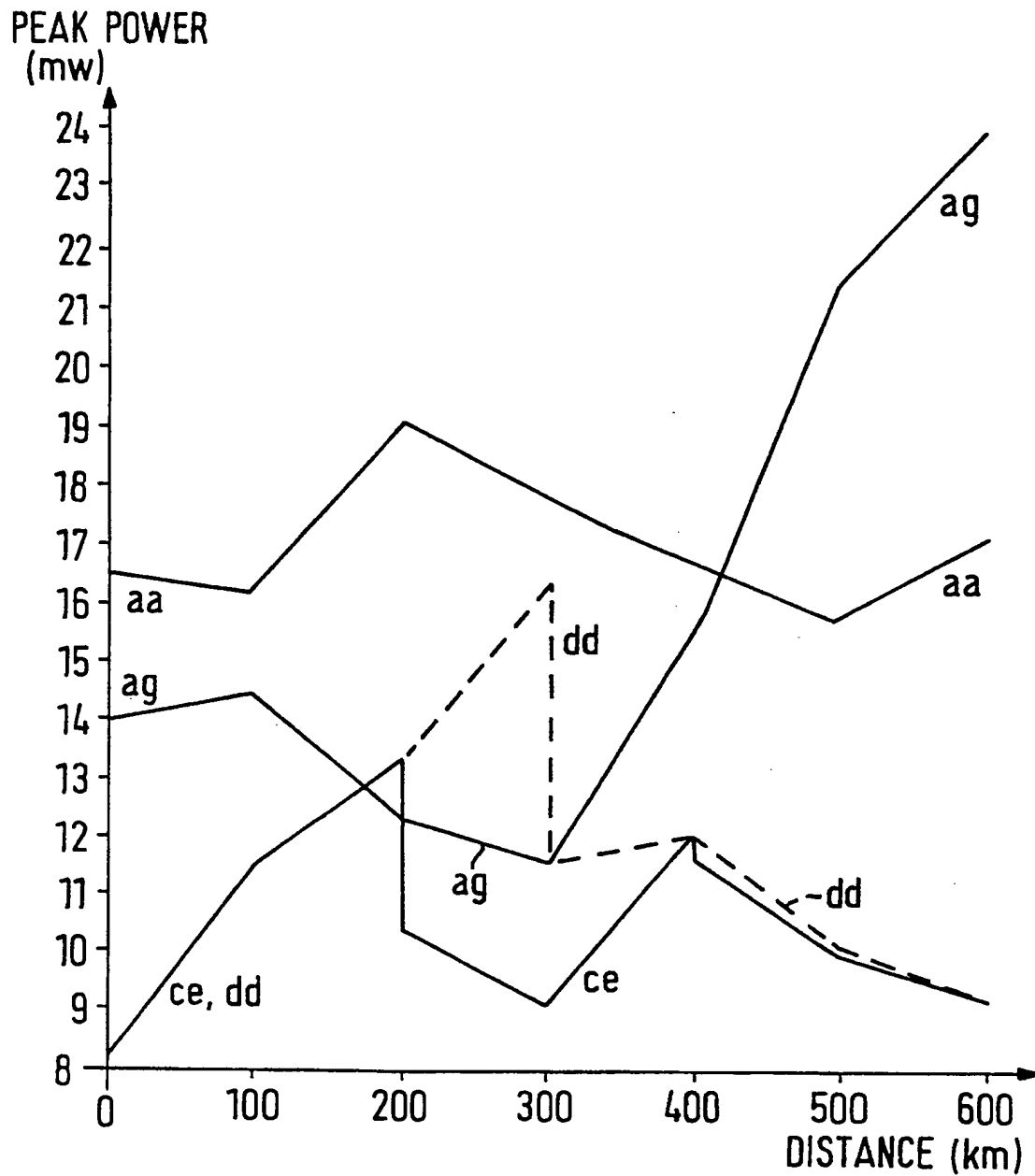


FIG. 3